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Further observations of large cumuliform clouds by the Meteorological Research Flight

by

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1. Summary

The results of nine flights made to investigate the structure of selected cumuliform clouds are discussed. These flights were designed to provide information on the variation of cloud parameters with time and space separately as distinct from the simultaneous variation characteristic of the flights reported in (1).

It is tentatively concluded that water contents of the order of 5.0 gm.m^{-3} exist in limited regions in the large convective clouds of temperate latitudes and that droplet coalescence plays an important part in the mechanism of shower production. Some support is found for the "bubble" theory of convective cloud structure.

2. Introduction

Since the life of the average cumulus cell is about 30 min. and a horizontal traverse of the cloud by an aircraft occupies about 5 min. it is not possible to obtain detailed information of the development of the whole cell with one aircraft. It therefore becomes necessary to restrict the investigation to one level and ultimately to combine the results of several series of investigations each restricted to a particular region of the cloud.

In this series, therefore, each flight was concerned with a particular level within the top third of an initially well developed cumulus cloud. In some cases radar echoes from the cloud were photographed by the East Hill Weather Radar station (near Dunstable, Beds.).

Since the data accumulated in this study are very extensive it has not been possible to discuss them in detail in this paper which should be regarded as a preliminary summary of the main findings. It is hoped in the future to supplement this paper with a series of supporting papers each dealing with one of the main aspects of the work in greater detail than is here possible, and drawing on the further results of the continuing investigation.

3. Aircraft instrumentation

This was in the main similar to that discussed in (1) i.e., measurements were made of temperature, humidity, height, airspeed, vertical acceleration, water content, rate of icing, size and nature of particles. There were certain improvements in technique:-

(i) Except for the size and nature of particles and vertical acceleration all the quantities measured were displayed on an automatic observer panel and photographed at 5 sec. intervals throughout the traverse.

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(ii) Humidity of the environment was measured with an automatic frost-point hygrometer of the type described in (2), as well as with the manual frost-point hygrometer.

(iii) Vertical motion of the aircraft was obtained in some cases by integration of the accelerometer trace and in the remainder by a modification of the method used in (3). This matter is discussed further below.

(iv) Temperature measurements were made with an axial vortex thermometer of the type described in (4). This instrument has limitations when used in cloud, particularly in icing conditions, but its use represents an advance on that of the flat plate type. There is further discussion of this aspect below.

(v) After several tests in flight and in the wind tunnel it was decided to use oil as the sampling medium in droplet-impactors rather than magnesium oxide since oil permits the sampling of considerably larger droplets and also avoids the necessity for an empirical relationship between size of crater and size of droplet. The system at present in use still has a number of defects which are discussed further below.

4. Operational procedure

It was customary for the aircraft to climb from base towards East Hill, observations being made of temperature and frost-point at 500 ft. vertical intervals throughout the layer affected by convection. Visual observations of cloud were made as appropriate.

In the vicinity of East Hill a cumulus cloud approaching maturity and reasonably isolated from its neighbours was selected and identified by the East Hill radar. Traverses through cloud were made as far as possible between the same two air positions and at a constant nominal height which was chosen so that a representative range of temperature should be covered in the series of investigations. Traverses were commenced about 5 min. after the cloud had appeared at the height of the traverse and continued until the cloud could no longer be positively identified or until it had passed through at least one cycle of growth and decay. During each traverse observations were commenced 1 to 2 min. before cloud was entered and continued for a similar period after it had been left; photographs were taken of the cloud as it was approached.

During the traverses East Hill radar maintained a watch on the cloud under investigation and Farnborough long range radar maintained a safety watch on the aircraft.

5. Treatment of results

Each flight has been analysed separately and in considerable detail but it is obviously not possible to present the separate analyses in a paper of this type. For the purpose of this preliminary report it has been considered more suitable to summarise the measurements in tables of mean and extreme values of the more important parameters. These tables, numbered 1 to 9, are given in an appendix.

In subsequent sections the individual analyses have been considered as a whole and the data discussed with particular reference to the following topics:-

a. General - including structure, life cycle, heights of base and top of the clouds examined and their relation to relevant soundings

b. Composition

c. Vertical motions and turbulence

d. Water content and icing

e. Temperature

f. Additional information

the interpretation of the observed facts being a provisional one. Each of these sections is now considered in detail:-

General

(i) Structure. The clouds investigated usually consisted of a cloudy region of small water content, small and randomly distributed vertical motions, and low droplet concentrations, in which was set an actively developing entity of higher water content and organized vertical motion. These active regions, which are sharply defined, are termed cells.

Usually only one cell was encountered during a traverse, the diameter of which was so large in comparison with the diameter of the cloud as to make it evident that there was in fact only one cell present. On two occasions, however, the aircraft passed through two separate cells, and it is impossible to be certain that these were the only ones in the cloud.

Cells usually had a horizontal dimension of 2 to 3 mi. but exceptionally they were as large as 5 mi. or as small as 1 mi. Where there was more than one cell, they were never more than 2.5 mi. across.

The cloudy region around the cell was of varying horizontal dimension and the cell was usually asymmetrically situated in it. The general trend with time was for the cloud to be identical with the cell at first and for the surrounding cloudy region to grow with time during the development of the cloud. Generally the cloudy region was much narrower on one side of the cell than the other.

Horizontal dimensions of the cloudy regions were usually 0.5 to 1 mi. on the narrow side, and 2 to 5 mi. on the wide side, though on occasions the wide region was between 4 and 7 mi. across.

(ii) Life cycle. The usual life cycle of the cell appears to be between 20 and 25 min. rising occasionally to 30 to 35 min. In the case of the cell of small horizontal dimension the life may be between 10 and 15 min. This is consistent with the erosion process proposed in (5).

(iii) Bases and tops. The cloud observations made are summarised in Table 10 together with the base and top levels calculated by the "parcel method". The height of base was obtained from the temperature and humidity observed at the nearest synoptic station, while the height of the tops was deduced entirely from the temperatures at the base of the cloud and above, as observed from the aircraft. The calculated heights of base were in error by between 200 and 1,700 ft. in either direction, the most frequent errors being about 550 ft. above the observed level and about 1,100 ft. below.

Determinations of the level of tops can often be made very accurately when one allows for the fact that quite small variations in the stability of the environment are often sufficient to stop the vertical development, but when the parcel method is applied strictly errors of several thousand feet may easily be made. The conclusion is that the excess of virtual temperature suggested by the parcel method is not realised throughout the entire cloud and that near the top the cloud is of considerably lower buoyancy than might be expected. In such conditions small stabilisations of the temperature-lapse would be sufficient to retard development.

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On several occasions the atmosphere became very dry above 10,000 ft. but this does not seem to have retarded development. It appears from this that entrainment into the upper portion of a cloud is not a significant feature in vertical development and, therefore, that it is of small magnitude.

(iv) Other clouds. On most occasions thin layers of stratocumulus and altocumulus lay around the cumulus. These layers were invariably to be found at the base of a shallow region of stabilisation of the temperature-lapse revealed by the aircraft sounding though not shown in the routine radio-sonde sounding. On a few occasions a very thin layer of cirrostratus was observed at the level of the highest tops and this again was usually to be found in such a region of greater stability.

On a very few occasions there was a shear in the vertical of the horizontal wind field some 50 mb. below the stratocumulus layer.

Observations of layer cloud are summarised in Table 11.

The findings above, though more detailed, agree broadly with those of (1). There is a divergence on the accuracy of the forecasts of base and tops though this may be ascribed to small personal errors in the application of the parcel method, emphasising the large subjective element in its application.

Composition

(i) Certain comments are necessary in respect of the sampling of cloud-particles:-

Tests in the wind tunnel of all the types of impactor used by M.R.F. during the past four years suggest that these instruments are affected by splash to some extent, particularly in clouds of high water content and when the period of exposure is long.

A further defect arises when ice crystal or mixed water droplet and ice crystal clouds are sampled, since, unless precautions are taken to maintain the sampling oil at a temperature below 32°F. until the sample has been photographed, many of the ice crystals melt and spurious distributions of droplet diameter result (6).

Both defects lead to distributions falsely biased toward the larger droplet diameters. Improvements subsequent to this work have largely eliminated errors arising from splash, and development of the microphotographic equipment by Abel (6) has shown how the melting of sampled ice crystals may be avoided.

In the examination, therefore, of droplet samples care has been taken to reject all those which may have been affected by splash or by the melting of crystals. As a result droplet information is biased toward pure droplet cloud and clouds of low water content and generalisation from this evidence is difficult.

Some representative drop-size spectra are shown in Fig.3 and a brief statement of the distribution of droplet diameters as observed in each flight is given in Tables 1 to 9.

Within the limitations of the sampling system, and those imposed by the considerable scatter of the results, it appears that, in the top third of the clouds examined and between the temperatures 0° and 18°F., droplets were most numerous and most uniform in size in the body of the cloud early in development. In the later stages the droplet-size spectra

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became "stepped" - suggestive of coalescence - and the concentration of droplets less, the largest droplets then being observed in updraught regions. At the edges of the cloud droplet spectra were usually not stepped and concentrations and diameters much less than in the body of the cloud. Variations in both diameter and concentration were often very great over distances of the order of 500 ft.

Maximum droplet diameters in the body of these clouds were about 40 μ at first and became 60 to 80 μ about five min. after the cloud had appeared at the height of traverse; 5 min. later droplet diameters of 60 to 80 μ were common and those of 90 to 120 μ were often observed, this latter range of sizes becoming common a further 5 min. later. Diameters of 120 μ were rarely exceeded but observations of droplet diameters of up to 350 μ have been made.

(ii) The technique at present in use at M.R.F. for the sampling of ice crystals is the "replica" technique due to Schaefer (7). As used at M.R.F. it is thought that the crystals are damaged in the sampling process and that the strength of the sampling solution used had been incorrectly chosen. Information provided by crystal sampling in these flights therefore, is limited to occurrence and probable size. Within the temperature range concerned in these flights crystals rarely appeared less than 10 min. after appearance of the cloud at the height of the traverse but usually grew rapidly thereafter, often reaching overall diameters of 50 μ in periods of the order of 5 min. The subsequent aggregation of simple crystals into snow appeared to take much longer.

Crystals were rarely observed at temperatures above 10°F.; when they were, it was late in the life of the cloud when degeneration was advanced. At temperatures below 10°F. crystals were numerous and appeared early in the life of the cloud, though Flight 4 was anomalous in that no crystals were observed although the temperatures observed were between 5 and 9°F. This must presumably be ascribed to a lack of freezing nuclei on this occasion. These observations agree well with those of (8a).

(iii) In general it is probable that the usual rain-producing mechanism in these convective clouds was a combination of the Bergeron and coalescence mechanisms. The usual process appears to have been the rapid growth of cloud droplets by coalescence to about 100 μ diameter in 8 to 10 min. after the appearance of the cloud at the height of the traverse, and the onset of crystallization at temperatures below 10°F. thereafter. The aggregation of simple crystals in the development of the snow stage and subsequent production of rain seemed to take about 15 to 20 min. after the initial appearance of droplets of 100 μ diameter. Where coalescence alone operated the mechanism usually took about 15 to 20 min. to produce rain at the height of the traverse.

Droplet-diameters of 100 μ appeared to be critical in rain production where the Bergeron mechanism operated; it is suggested that this diameter is associated with the probability of nucleation at the temperatures commonly associated with shower production (8b).

Summarising then, the Bergeron mechanism appeared to operate at temperatures below 10°F. and through the intermediate formation of droplets of about 100 μ diameter by the coalescence process, the whole process taking about 30 min. At temperatures higher than 20°F., production of rain seemed to be by the coalescence mechanism alone and the process took about 20 min. Between 10° and 20°F. the coalescence process predominated in the production of rain and the Bergeron mechanism commenced late in the life of the cloud and tended to assist in its dissipation.

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A similar conclusion reached by Murgatroyd (9) was based on the fact that mean temperatures of crystallisation of cumuliform clouds are in the range 0° to 10°F. whereas according to the data in (10) the mean temperature in the tops of cumuliform clouds which produce rainfall is of the order of 20°F.

Vertical motions and turbulence

The problem of obtaining information about the field of vertical motion through which an aircraft passes is of extreme difficulty. It was customary earlier (1) to obtain vertical velocity from the record of the aircraft's height and airspeed, thus following the procedure used in Project Thunderstorm (3) but this is a rather crude method and at best yields values of vertical velocity averaged over 5 sec. intervals.

Two methods of computing vertical velocity have been used in this series of flights. In the first, vertical velocities have been derived from height and airspeed variations, but with allowance made for changes in aircraft attitude in the pitching plane by reference to the results of a secondary experiment. In this latter experiment the change in airspeed after various intervals consequent on a sudden change of attitude was determined in nominally still air. Again the information is coarse and rather inaccurate but all observations are used whereas in (1) those in which airspeed varied were rejected.

The second method was used for those flights for which accelerometer traces were available. If it is assumed that an aircraft responds instantaneously and accurately to the vertical velocity field through which it moves, and further that an accelerometer mounted at the centre of gravity of the aircraft responds similarly to consequent vertical accelerations of the aircraft, then the vertical velocity field may be obtained by simple integration of the accelerometer trace. This is the method adopted; a similar one was used by R.F. Jones (11).

In fact the response of an aeroplane to a gust of the simplest form is extremely complicated and the response of available accelerometers to a series of accelerations is far from accurate. The present position is that even were an ideal accelerometer and the complete range of aerodynamic constants for the aircraft used, and the variations of aircraft speed and attitude known, the field of vertical motion could still not be computed, even at considerable expenditure of effort, because of other uncertain factors arising from aircraft structural response. The problem has been reviewed recently in (12) and (13).

Since no better method at present exists we have assumed in the present series of flights that the velocity can be obtained by simple integration of recorded acceleration. Although the procedure is at best inaccurate, it appears that the inaccuracies are likely to be smaller than those inherent in the first method and that, in particular, the fine structure of the field of vertical velocity will be more accurately given. The conservative nature of the form of the integral trace in some of the flights is taken to support this view.

Within these limitations, then:-

(i) The maximum updraught observed was about 32 ft. sec.$^{-1}$ and the maximum downdraught about 40 ft. sec.$^{-1}$. The average maximum strengths were 23 ft. sec.$^{-1}$ upwards and 21 ft. sec.$^{-1}$ downwards. Mean vertical motions over the whole cloud width ranged from about 1 ft. sec.$^{-1}$ in both senses in advanced decay to about 10 ft. sec.$^{-1}$ in both senses at the peak of development. Motions were usually clearly defined in growth but weak and randomly distributed in decay, save where there was precipitation when downwards motions were well organized. At the onset of decay there was often a very rapid change from predominantly upward to predominantly downward motion.

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On most occasions significant vertical motions were confined to cloud and they were of similar strength and horizontal extent irrespective of sense. On a few occasions there were vertical motions outside the cloud which were of comparable strength and horizontal extent to those within. These were apparently associated with the cloud, since they occurred only in air fairly close to it, and were usually encountered during the decay of the cloud. Some clouds were composed of a well defined draught and had weak compensating motions around them. These were the cases where a sudden change in the sense of motion occurred at the onset of decay and the clouds were invariably single celled.

In some cases, then, there appeared to be little interaction between the cloud and its environment in the region of the investigation - the upper third of the cloud; in a few cases there was an interaction and these were usually multi-celled clouds.

In general the draught had a horizontal dimension of about 1 to 2 mi. with fine structure on the scale of 500 to 1,000 ft., many features of which were conserved from one traverse to the next. It seems reasonable to regard the draught as defining the cloud cell and to attribute the fine structure to the presence of convection bubbles constituting the cell.

There is some evidence to suggest that fresh development was usually on the upshear side of the cloud.

(ii) Turbulence was invariably greatest in the cloud; vertical accelerations rarely exceeded 0.5g. (at 170 kt.) and were usually about 0.2g. The maximum value observed was 0.7g. These accelerations were almost invariably associated with regions of high horizontal gradient of vertical velocity and therefore with multi-celled clouds or single-celled clouds near maturity.

These conclusions are in agreement with those of (1) though more detailed. They appear to accord well with (5) though the difficulty of measuring vertical motion in cloud is reflected in the imprecision of most of the conclusions.

Water content and icing

(i) The maximum water content of clouds which could be measured by M.R.F. at this time was about 2gm.m^{-3} with the rotating disc icing meter and about 1.8gm.m^{-3} with the heated cylinder instrument. The maximum theoretical water content which is to be expected in convective clouds of temperate latitudes is of the order of 5 gm.m^{-3} but such values should be fairly limited in space and probably time, and the available instruments have sufficient capacity for the great majority of encounters.

For the flights of this series each observation of water content or icing rate has been reduced to a percentage of the maximum theoretical amount to be expected on the occasion, and its position given as a percentage of the cloud width and depth. On the basis of these figures a smooth non-dimensional model has been constructed and from it computed the distribution of water content to be expected in a convective cloud having its base at 900 mb. and a temperature of 60°F. and its top at 400 mb.; these models are given in Figs. 1 and 2 respectively, and have previously been discussed by Murgatroyd (9). The water content contours shown are similar to these given by Zaitsev (14).

From Fig. 2 it is seen that water contents of the order of 5 gm.m^{-3} might be expected in a central region of such a cloud at a height of about 75% of the cloud depth (about 16,000 ft.) and extending over about 25% of cloud width (about 1 mi.). A fairly uniform gradient of water

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content is found over the greater portion of the cloud but greatly increased gradients are found in the outer regions. At the vertical edges and at the base the increased gradients extend over a thickness of about 8%, whilst at the top the gradient in the uppermost 25% is notably greater than elsewhere in the cloud, again increasing markedly in the uppermost 4% of cloud depth.

These findings are somewhat similar to those of (1), but of more exact form. It seems likely that there is support here for (5) and that the outermost regions of high gradient of water content may be ascribed to those in which the purely aerodynamic erosion forces operate, the thinner uppermost surface being consistent with the continual renewal of this region from within the cell. It seems possible that the slacker internal gradients may be ascribed to diffusion of the modified boundary air into the main body of the cloud.

Detailed examination of the individual flights shows that water contents approaching the maximum theoretical amount may be encountered more than once during the life of a particular cloud; in Flight 7, such values were found for almost the whole life -about 20 min.- of the cloud, which produced a shower by the coalescence mechanism.

It must be mentioned that the later conclusions above are dependent on the assumption that all flights passed through the central region of the cloud: any transverse displacement of the flight path introduces an uncertainty. Such a shift of flight path undoubtedly occurs in some instances though it is not felt that the general conclusions are invalidated in any way. When more flights of this type have been made a non-dimensional approach to the time variation such as that applied to the space variation will be possible.

(ii) Airframe icing was encountered at temperatures between 28° and 7°F. (no flights were made at temperatures below the latter value). Icing was encountered during the greater part of the life of the convective cell and it appeared, therefore, that material advance of glaciation normally heralded a rapid decay. A noteworthy observation was that of heavy icing over a period of about 57 min. at a temperature of about 7°F. during Flight 4; this period is much in excess of those normally observed by M.R.F. and must presumably be associated with a deficiency of freezing nuclei.

It seems, then, that in cumulus such as those investigated the probability of icing is high during the greater part of their lives, but becomes small when decay commences. Whilst ice accretion will normally be small due to the small horizontal extent of the cloud it may on occasions be large where extremely high values of water-content are encountered.

Temperature

It seems likely that in droplet cloud above freezing point a vortex thermometer of the type used consistently under-reads by a small amount but that in icing conditions its behaviour is not straightforward. In the flights of this series icing conditions were common and excesses over environment temperature consistent with parcel method calculations were observed. The temperature traces show peaks which are roughly symmetrical with respect to the cell which suggests that any reduction in amount of correction due to the partial blocking of the entry by ice did not contribute to the apparent temperature rise in cloud, i.e. it must to a certain extent have been real. It seems reasonable, then, to accept the indicated cloud temperatures as minima accurate to at least 1 or 2°F.

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In general it appeared that in the earliest stages of growth there was invariably a good agreement between the strength and direction of vertical motions and the excess or deficit of cloud-temperature over environment-temperature. Where the structure of the cloud was simple the agreement became less good as maturity was approached and weakly negative as decay became established.

Where the cloud structure was complicated the agreement very rapidly ceased to be good and there then appeared to be no relation between temperature contrasts and the vertical motion.

A typical variation of temperature excess appeared to be a steady increase from 0.3° to 2.5°F. during growth, (the corresponding excess to be expected from calculation by the parcel method being about 5°F.) and a fairly rapid decrease to about -1.5°F. in decay, the whole process taking about 25 min. Updraughts were warmer than the rest of the cloud which was usually warmer than the environment by a similar amount so that the excess of temperature in the updraught was probably about the value to be expected from the parcel method except near the top of the cloud.

An attempt was made by Murgatroyd (9), on the basis of the observations of this series of flights, to obtain a relationship between the vertical velocity, w ft.sec.$^{-1}$, and the excess of virtual temperature, Δ T°F. - corrected for the weight of suspended water -, and a relationship

$$w = 14 \sqrt{\Delta T}$$

was suggested. There was a large scatter of the observations due to their small number but it seems that this will be a profitable avenue of enquiry when more observations with better instruments are available.

Other observations

(i) The clouds investigated were of a simpler structure generally than those reported in (1) and electrical activity was small. Precipitation static was reported early in Flights 2, 3 and 9, which were made through multi-celled clouds in which droplets of about 100 μ diameter or larger co-existed with crystals about 50 μ in diameter or larger. These observations are consistent with the hypothesis that electrical activity is characteristic of clouds in which the Bergeron and the coalescence mechanism of rain production are both operating, as suggested by workers at the New Mexico School of Mines (19) and others.

(ii) Radar echoes were observed from the cloud of Flight 2 alone. This contained snow for a considerable period but other clouds not giving an echo also had a snow stage though not so marked. The cloud of Flight 2 is distinguished from the others of the series in that it contained an appreciable fraction of droplets of diameter between 100 and 200 μ .

(iii) Visibility in cloud was usually estimated to be 5 to 20 yd. in periods of growth and rose to 100 to 300 yd. in decay. The smallest visibilities were observed where there was a large number of the very small droplets.

Tests of Trabert's formula, as modified by Best (18), using measured water contents and droplet diameters and estimated visibilities, when these were obtained simultaneously, suggested that the calculated visibilities were probably too great by a factor of about three. Visibilities used were those less than the semi-span of the aircraft and the estimates should be reasonably accurate. The number of these observations is rather small at present and they are biased towards small visibilities so that a definite statement on this matter is not justified.

7. Discussion

As was stated in (1) the object of this work is to obtain a knowledge of the various cloud parameters and the manner in which they develop during the life of the cloud.

Since the work reported in (1) the technique of investigation has been improved though it is still inadequate. It is obvious that several more such series of flights will be necessary, each devoted to a particular region of the cloud, in order that the generalisations made above may be extended from the upper portion of the cloud to the whole structure. Without a very large aircraft commitment and a complex organization of research it is inevitable that information will remain largely statistical and indeed this seems desirable as the considerable differences between clouds prevent progress by the complete investigation of a very few clouds. An investigation blending the type of observation described in (1) and those described above will obviously be ultimately necessary.

In the instrumental field it has become obvious that considerable difficulties exist particularly in the measurement of temperature and vertical motion and the sampling of ice crystals. Although in the flights reported above the measurement of water content was satisfactory it has recently been improved considerably at M.R.F. by the introduction of a heated wire water content meter and a refrigerated rotating disc icing meter. Moderately detailed observations of liquid water content up to 5.0 gm.m^{-3} are now possible and amounts up to 2.5 gm.m^{-3} may now be measured on the scale of about 800 ft.

Sampling of cloud droplets and raindrops has been refined considerably since this series of flights but that of ice crystals is still not satisfactory. Although no progress is expected immediately in the measurement of temperature and vertical motion it is hoped that methods currently being explored will prove profitable.

8. Conclusions

The more important features of the large convective cloud over southern England suggested by these flights appear to be:-

a. The importance of the coalescence mechanism in advance of the Bergeron mechanism in shower production and the possibility that on occasions the coalescence mechanism alone may operate at the higher temperatures in these latitudes.

b. The probability that water contents approaching 5.0 gm.m^{-3} exist in these clouds over a small region in time and space. This has since been directly confirmed by the author (17).

c. The association of turbulence in cloud with strong gradients of vertical motion and hence with multi-celled clouds or simple clouds entering the precipitation stage.

d. Support, from measurements of vertical motion and of water content, for the structure of convective cloud in accord with the "bubble" theory.

e. The absence of marked vertical motions outside cloud and the balance of vertical motions within the cloud, suggesting a rather weak interaction of the cloud with its environment, that is, small entrainment and detrainment motions. There is some support for this contention from radar observations.

f. The dependence of electrical activity on the co-existence of large droplets and large crystals in the cloud.

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These conclusions are in general agreement with those of (1) and it is hoped that they will be examined in the future at greater length together with data from further flights of this nature in a series of supplementary papers.

9. Acknowledgments

Acknowledgment is due to those members of M.R.F. who assisted in the basic analysis of the formidable body of data accumulated and in particular to Mr. R.J. Murgatroyd, S. Met. O., M.R.F., who made several of the suggestions on which this work is based and who participated in the detailed analysis.

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Table 1

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Main features of cloud investigated in Flight 1

Run	1	2	3	4	5	6
Maximum water content, gm.m^{-3}	1.06	> 1.8	> 1.8	> 1.8	> 1.8	> 1.8
Mean water content, gm.m^{-3}	0.30	0.37	0.64	0.59	0.60	0.33
Icing, Yes or No	Yes	Yes	Yes, 1/16in. clear on airframe	Yes, on airframe	Yes, clear airframe, windscreen	Yes, windscreen
Mean height, ft. (ICAN)	13,870	13,640	13,537	13,544	12,965	12,446
Height variation, ft.	+20 -30	+120 -130	+113 -77	+206 -64	+685 -435	+124 -166
Mean airspeed, kt.	182	174	181	172	180	179
Airspeed variation, kt.	+3 -2	+8 -4	+5 -7	+10 -14	+10 -10	+6 -4
Mean temperature, °F.	+18.1	+18.2	+19.3	+18.1	+16.5	+16.1
Temperature variation, °F.	+1.8 -1.2	+0.9 -1.4	+1.7 -2.6	+0.6 -1.0	+2.5 -2.3	+1.5 -1.3
Maximum excess temperature in cloud, °F.	1.4	1.0	In updraught 2.8 In downdraught -1.5	In updraught 0.9 In downdraught -0.5	In updraught 2.2 In downdraught -2.1	In updraught 1.4 In downdraught -1.5
Average turbulence in cloud, 'g'	0.1-0.2	Not observed		0.1-0.2	0.1-0.2	0.1-0.2

/Precipitation

Run	1	2	3	4	5	6
Precipitation static, Yes or No	No	No	No	No	No	No
Vertical velocity strength. Peak:- ft.sec^{-1}	(+3 (-4	+25 - 8	+14 -13	+31 -38	+27 -22	+5 -6
Average:-	(+1½ (-2½	+7 -5	+ 8 - 7	+12 -10	+11 - 9	+2¼ -3½
(+ve. sign indicates updraught) (-ve. sign indicates downdraught)	Up on west side Down on east.	Mostly up	Whole cloud descending, save for narrow central core 2.5 mi. across	Mostly descending, narrow central core 0.8 mi. across	Generally down, a wide, new ascending cell	Small but mainly down
Crystals. Yes, No	Not observed.	Not observed	Not observed	Not observed	Not observed	Not observed
Other observations	-	-	Cloud rising fast	-	Whole cloud rising	Visibility 5yd.
Time, hr.	1616	1619	1624	1629	1632	1638
Extent, mi.	1.8	4.9	2.6 -0.6 Very tenuous to east	2.4 -0.8 Very tenuous to east	8.0 1.5 old cloud, 3.0 new cloud, rest wispy	10.4 2.0 old cloud, 1.0 new cloud, rest wispy
Droplet diameter μ Volume median:-) at edge maximum:-) Distribution stepped at:-)	50 100		20 200 80%, 40-150 μ	30 100	12 100 20%, 80 μ	
Droplet diameter μ Volume median:-) at centre maximum:-) Distribution stepped at:-)	30 300 30%, 80-120 μ		250 300 30%, 80-230 μ	150 200 40%, 80-140 μ	130 200 40%, 50-120 μ	

Table 2

8/7/53

Main features of cloud investigated in Flight 2

Run	3	4	5	6	7	8
Maximum water content, gm.m^{-3}	Highest to west 1.37	Highest to east 1.7	Highest to east 0.78	Highest to east > 1.8	Highest to west > 1.8	Highest to east 0.92
Mean water content, gm.m^{-3}	0.75	0.58	0.32	0.46	0.61	0.51
Icing. Yes or No	Yes, clear airframe and windscreen	Yes, heavy clear windscreen and airframe	Yes, heavy on airframe	Yes, rough white on airframe	No	Yes, slight on airframe
Mean height, ft. (ICAN)	10,332	10,110	10,210	10,234	10,147	10,137
Height variation, ft.	+138 -132	+160 -135	+120 -160	+166 -84	+73 -67	+33 -17
Mean airspeed, kt.	173	175	182	173	179	175
Airspeed variation, kt.	+ 7 - 8	+ 10 - 8	+ 6 - 5	+10 - 3	+ 7 - 6	+ 5 - 3
Mean temperature, °F.	21.4	20.8	19.8	19.8	20.6	20.5
Temperature variation, °F.	+1.8 -1.6	+1.1 -1.0	+0.7 -1.3	+0.7 -0.6	+1.9 -1.4	- -
Maximum excess temperature in cloud, °F.	1.2 -0.7 in down-draught	0.3 -0.7 in down-draught	0.1 -0.3 in down-draught	0.4	-	-

Runs 1 and 2 lost through faulty recording gear

/Precipitation

Run	3	4	5	6	7	8
Precipitation static, Yes or No	Yes, intermittent	Yes, intermittent	Yes, continuous	Yes, continuous	No	No
Vertical velocity strength. Peak:- ft.sec^{-1}	+12.8 - 5.3	+7.2 -13.1	+7.9 -4.1	+12.0 - 2.4	+5.0 -6.0	- -
(+ve. sign denotes updraught) Average:- (-ve. sign denotes downdraught)	+ 6.4 - 2.6	+3.4 -7.2	+3.3 -1.8	+ 4.8 - 1.2	+2.1 -3.6	- -
Average over run:-	3.8 up	3.1 down	2.6 up	3.6 up	1.0 down	-
Crystals. Yes or No	Not observed	Not observed	Yes	Yes	Yes	Yes
Other observations	Vis. 20 yd.	Vis. 50 yd.	Vis. 100 yd.		Vis. 300 yd.	Vis. > 200 yd.
Time, hr.	1600	1607	1615	1622	1631	1637
Extent, mi.	4.5	> 5.0	> 7.8	> 7.8	> 7.6	-
Droplet diameter μ Volume median:-) at centre	40-45	20-150	20-25	50	20-30	
Droplet diameter μ maximum:-) at centre	60-100	200-300	60-100	occ. 240	120	
Droplet diameter μ Volume median:-) at edge	20			26		
Droplet diameter μ maximum:-) at edge				40-60		
Remarks	Radar echoes, pptn. static coincides with snow region	Radar echoes, pptn. static coincides with snow region. Cloud very thin at edge	Radar echoes, pptn. static much stronger, cloud fibrous and decaying	Radar echoes, pptn. static much stronger, cloud very fibrous	No echo. Cloud fibrous and decaying markedly	Cloud degenerated

Table 3

14/7/53

Main features of cloud investigated in Flight 3

Run	1	2	3	4
Maximum water content, gm.m^{-3}	1.50	1.25	1.36	1.15
Mean water content, gm.m^{-3}	0.77	0.42	0.33	0.58
Icing. Yes or No	No	Yes	No	Yes
Mean height, ft. (ICAN)	15028	15339	15430	15520
Height variation, ft.	+ 97 -103	+61 -69	+130 -100	+260 -180
Mean airspeed, kt.	173	173	171	171
Airspeed variation, kt.	+ 7 - 9	+ 5 - 5	+ 9 -10	+ 4 - 5
Mean temperature, °F.	10.0	6.7	7.6	4.2
Temperature variation, °F.	+1.7 -2.1	+2.0 -1.0	+4.9 -1.2	+0.7 -0.7
Maximum excess temp. in cloud, °F	+3.7	+2.1	+6.1	+2.0
Average turbulence in cloud, 'g'	0.2-0.4	0.2-0.3	0.2-0.6	0.2-0.5
Precipitation static. Yes or No	No	No	Yes	No
Vertical velocity strength. Peak:- ft.sec.$^{-1}$	+12 -15	+17 -9.5	+ 9 -10	+ 9 - 5
Average:- Cell (a)	+5.4 -6.2	+9 -5.1	+3.2 -4.1	+4 -2.5
Average:- Cell (b)	+4 -1.8			
Crystals. Yes or No	Yes	Yes	Yes	Yes
Other observations	Vis. 20 yd. Freezing rain	Ice 1/8 in. rough white	-	Ice 1/8 in. rough white, small hail
Time, hr.	1651	1657	1701	1709
Extent, mi.	4.6	3.0	5.2	1.6
Droplet diameter μ — Volume median:- at centre of cell	75	65	75	85
Droplet diameter μ — maximum:- at centre of cell	120	110	130 (occ.220) 40%, 50 μ	110
Droplet diameter μ — Distribution stepped at:- at centre of cell				
Droplet diameter μ — Volume median:- at edge		23	20	23
Droplet diameter μ — maximum:- at edge		35	50	110

Table 4(a)

14/4/53

Main features of cloud investigated in Flight 4

Run	Cell	1	2	3	4	5
Maximum water content, gm.m^{-3}	1 2	> 1.7 0.64	1.06 0.39	> 1.8	> 1.8	1.36
Mean water content, gm.m^{-3}	1 2	0.20 0.62	0.12 0.32	0.75	0.64	0.40
Icing. Yes or No (both cells)		Yes, heavy	Yes, heavy	Yes, heavy	Yes, heavy	Yes, heavy
Mean height, ft. (ICAN)	1 2	8999 9048	8946 8978	9162	9204	8998
Height variation, ft.	1 1 2 2	+202 - 68 + 21 - 19	+ 32 - 28 + 4 - 6	+ 58 -112	+16 -14	+52 -18
Mean airspeed, kt.	1 2	179 170	172 171	182	184	179
Airspeed variation, kt.	1 1 2 2	+ 10 - 4 + 1 - 1	+ 4 - 4 + 8 - 5	+ 8 - 5	+ 8 - 8	+ 9 - 4
Mean temperature, °F.	1 2	+8.3 +4.4	+5.0 +7.5	+6.8	+7.3	+7.7
Temperature variation, °F.	1 1 2 2	+4.0 -3.2 +3.2 -1.0	+2.5 -0.9 +2.0 -0.8	+2.7 -3.6	+2.1 -2.5	+2.3 -2.7

/Maximum

Run	Cell	1	2	3	4	5
Maximum excess temperature in cloud, °F.	Both	1.8 in updraught -2.0 in downdraught	3.0 in updraught -2.4 in downdraught	+2.0 in downdraught	4.7 in updraught -0.8 in downdraught	3.5 in updraught
Average turbulence in cloud, 'g'	Both	0.1 - 0.2, occasionally 0.3	0.1 - 0.2, occasionally 0.3	0.1, occasionally 0.2 - 0.3	0.1, occasionally 0.2 - 0.3	0.1, occasionally 0.2 - 0.3
Precipitation static. Yes or No	Both	No	No	No	No	No
Vertical velocity strength. Peak:- ft. sec.$^{-1}$ (+ ve. sign denotes updraught) (- ve. sign denotes downdraught) Average:-	1 1 2 2 1 1 2 2	+ 10 - 40 0 - 4 + 3 - 3 0 - $2\frac{1}{2}$	+ 2 - 2 + 8 - 2 + 1 - $\frac{1}{2}$ + 4 - $1\frac{1}{2}$	+ 32 - 20 + 11 - $5\frac{1}{2}$	+ 6 - 2 + 2 - 1	+ 10 - 4 + 3 - 2
Crystals. Yes or No	Both	Not observed	Not observed	Not observed	Not observed	Not observed
Other observations		-	Freezing rain, 3/32 in. ice on props. and wings	-	-	Small hail, 1/16 in. rime and glazed ice
Time, hr.	Both	1147	1153	1200	1205	1212
Extent, mi.	1 2	3.1 2.0	2.6 2.1	4.0	2.8	3.5

/Droplet

Run			Cell	1	2	3	4	5
Droplet diameter μ	Volume median:-		1		135	105		310
			2			27		30
	maximum:-	at centre	1		150	220		340
			2			70		70
	Distribution stepped at:-		1		30%, 50-130 μ	50%, 110-180 μ		35%, 180-300 μ
			2					
	Volume median:-		1			23		
			2					
	maximum:-	at edge	1			70		
			2					
	Distribution stepped at:-		1			75%, 35-50 μ		
			2					

Run	Cell	6	7	8	9	10
Temperature variation, °F.	1 1 2 2	+1.2 -2.4	+2.4 -5.1 +3.3 -3.6	+2.0 -2.4 +1.7 -2.8	+1.2 -3.0 +1.3 -1.1	+1.5 -2.1
Maximum excess temperature in cloud, °F.	Both	4.2 in up-draught	1.3 in up-draught	4.6 in up-draught -1.2 in downdraught	4.6 in up-draught	3.6 in up-draught
Average turbulence in cloud, 'g'	Both	0.1 - 0.2, occasionally 0.3	0.2 - 0.3	0.1 - 0.2, occasionally 0.3	0.1 - 0.2	0.1 - 0.2, occasionally 0.3
Precipitation static. Yes or No	Both	No	No	No	No	No
Vertical velocity strength. Peak:- ft. sec^{-1}	1 1 2 2	+ 2 - 4 + 16 - 12	0 - 8 + 10 0	+ 2 - 2 + 1 - 2	0 - 6	+ 2 - 12
Average:- (+ ve. sign denotes updraught; - ve. sign denotes downdraught)	1 1 2 2	+ ½ - 2	0 - 3 + 4½ - 4	+ 2 - ½ + 3 0	0 - 5 + ½ - 1	+ ½ - 4
Crystals. Yes or No	Both	Not observed	Not observed	Not observed	Not observed	Not observed

/Other

Table 4(b)

14/4/53

Main features of cloud investigated in Flight 4

Run	Cell	6	7	8	9	10
Maximum water content gm.m.$^{-3}$	1 2	1.8	1.8	1.8	1.36 1.30	0.92
Mean water content gm.m.$^{-3}$	1 2	0.75	0.77 0.85	0.80 0.59	0.40 0.71	0.43
Icing. Yes or No	Both	Yes, heavy	Yes, heavy	Yes, heavy	Yes, heavy	Yes, light
Mean height, ft. (ICAN)	1 2	9213	9013 9000	8999 9016	8995 8998	9004
Height variation, ft.	1 1 2 2	+ 7 - 3 + 8 - 13	+ 6 - 5 + 5 - 3	+ 5 - 14 + 5 - 3	+ 7 - 14	+ 2 - 5
Mean airspeed, kt.	1 2	181	182 179	185 183	184 190	181
Airspeed variation, kt.	1 1 2 2	+ 4 - 2	+ 3 - 8 + 14 - 13	+ 5 - 4 + 4 - 3	+ 6 - 6 + 4 - 3	+ 9 - 7
Mean temperature, °F.	1 2	+7.0	+7.8 +6.6	+6.8 +8.5	+9.1 +7.3	+8.1

/Temperature

Run			Cell	6	7	8	9	10
Other observations					1/8 in. ice. Vis. 10 yd. Freezing rain	3/4 in. ice on leading edge. New cloud top developing	Freezing rain. 1 in. ice, rough	$1\frac{1}{2}$ in. ice
Time, hr.				1220	1230	1235	1244	1252
Extent, mi.			1 2	2.8	3.7 5.5	3.0 2.8	3.1 4.1	3.6
Droplet diameter μ	Volume median:-		1 2		160 30		15	
	maximum:-	at centre	1 2		180 70		35	
	Distribution stepped at:-		1 2		12%, 50-150 μ			
	Volume median:-		1 2				20	
	maximum:-	at edge	1 2				25	
	Distribution stepped at:-		1 2					

Table 5(a)

13/4/53

Main features of cloud investigated in Flight 5

Run	1	2	3	4	5
Maximum water content gm.m.$^{-3}$	1.36	> 1.7	1.06	1.06	0.78
Mean water content gm.m.$^{-3}$	0.40	0.98	0.48	0.47	0.24
Icing. Yes or No		Yes	Yes	Yes	Yes
Mean height, ft. (ICAN)	7746	7767	7740	7757	7746
Height variation, ft.	+ 4 - 6	+133 - 27	0 0	+ 23 - 7	+ 4 - 6
Mean airspeed, kt.	181	184	186	184	183
Airspeed variation, kt.	+ 6 - 10	+ 8 - 12	+ 4 - 6	+ 5 - 3	+ 7 - 2
Mean temperature, °F.	+16.0	+16.5	+17.8	+17.0	+18.2
Temperature variation, °F.	+1.2 -0.7	+0.6 -1.4	+2.0 -1.8	+0.7 -0.5	+1.4 -1.5
Maximum excess temperature in cloud, °F.	1.0	1.0	2.4		1.6
Average turbulence in cloud, 'g'	0.1	0.1	0.1	0.1	0.2
Precipitation static. Yes or No	No	No	No	No	No
Vertical velocity strength. ft. sec.$^{-1}$ Peak:-	(+ 10 (- 14	+ 26 - 8	+ 10 - 11	+ 11 - 5	+ 8 - 10
Average:-	(+3.0 (-3.5	+5.5 -3.5	+4.5 -4.0	+4.5 -2.5	+3.0 -4.0

/Crystals

Run		1	2	3	4	5
Crystals. Yes or No		Not observed	Not observed	Not observed	Not observed	Not observed
Other observations				Mixed, 3/32 in. thick. Rime and clear	Rime and clear ice mixed, 1/16 in. thick. Vis. 5 yd.	Clear ice 1/32 in. thick. Vis. 50 yd.
Time, min. from appearance of cloud at traverse height (1130Z)		0+5	0+12	0+19	0+27	0+34
Extent, mi.		6.0	7.4	2.8	2.6	2.3
Droplet diameter μ	Edge	Largest 50, most 20 or smaller	Mostly 20-10	Largest 50, most 10		
	Centre		Largest 85, mostly 20		Largest 80 most 35 or less	Largest 180 but occ. 320. Most 40-20

Table 5(b)

13/4/53

Main features of cloud investigated in Flight 5

Run	6	7	8	9
Maximum water content, gm.m.$^{-3}$	1.20	> 1.8	> 1.8	1.06
Mean water content, gm.m.$^{-3}$	0.74	0.66	0.75	0.36
Icing. Yes or No	Yes	Yes	Yes	Yes
Mean height, ft. (ICAN)	7743	7745	7748	7764
Height variation, ft.	+ 7 - 3	+ 5 - 5	+ 2 - 8	+ 96 -124
Mean airspeed, kt.	178	176	178	184
Airspeed variation, kt.	+ 4 - 8	+ 5 - 5	+ 4 - 4	+ 3 - 4
Mean temperature, °F.	+18.5	+17.1	+17.3	+18.5
Temperature variation, °F.	+0.6 -1.6	+1.1 -1.2	+0.6 -0.7	-0.7 -1.0
Maximum excess temperature in cloud, °F.	2.0	2.0	2.0	1.8
Average turbulence in cloud, 'g'	0.2	0.2	0.1	0.1
Precipitation static. Yes or No	No	No	No	No
Vertical velocity strength. ft. sec.$^{-1}$ Peak:-	+ 11 - 18	+ 6 - 5	+ 10 - 6	+ 11 - 20
Average:- (+ ve. sign denotes updraught) (- ve. sign denotes downdraught)	+4.5 -4.5	+4.0 -3.5	+4.0 -2.5	+3.5 -6.5

/Crystals

Run	6	7	8	9
Crystals. Yes or No	Not observed	Not observed	Not observed	Not observed
Other observations	Vis. 5 yd.	1/8 in. glazed ice. Vis. 5 yd.	Vis. 5 yd. 3/32 in. ice. Freezing rain	
Time, min. from appearance of cell at traverse height (1130Z)	0+43	0+50	0+56	0+62
Extent, mi.	2.0	2.7	3.0	2.3
Remarks	Tops flattening out.	Tops flattening, anvil to south		Tops fibrous
Droplet diameter μ — Edge		30 - 20	Largest 70, most 20	Largest 50, most 20 or less
Droplet diameter μ — Centre	Largest 80, most 20-30	Largest 50, most 30-20	Largest 120, most 30-20	Largest 120 but occ. 260. Most 20 or less

Table 6

4/6/53

Main features of cloud investigated in Flight 6

Run	1	2	3	4	5	6	7	8
Maximum water content, gm.m^{-3}	1.20	1.20	1.20	1.20		0.28	1.36	1.36
Mean water content, gm.m^{-3}	0.45	0.45	0.72	0.52	Recorder film fogged, record lost	0.09	0.34	0.52
Icing. Yes or No	Yes	Yes	Yes, slight	Yes, slight		Yes, very light	Yes	Yes, slight
Mean height, ft. (ICAN)	10248	10725	10883	10901		10724	10829	10746
Height variation, ft.	+ 52 - 28	+ 55 - 45	+ 57 - 43	+ 89 -101		+ 36 - 94	+ 91 - 98	+ 54 - 66
Mean airspeed, kt.	181	179	179	175		180	178	181
Airspeed variation, kt.	+ 5 - 3	+ 2 - 4	+ 3 - 2	+ 7 - 5		+ 3 - 3	+ 4 - 8	+ 1 - 2
Mean temperature, °F.	+15.4	+14.9	+15.5	+14.7		+16.6	+16.7	+16.7
Temperature variation, °F.	+0.6 -0.8	+0.4 -0.3	+1.0 -0.8	+0.6 -1.1		+0.4 -1.2	+0.9 -0.5	+0.7 -0.7
Maximum excess temperature in cloud, °F.	1.1 in up-draught		1.3 in up-draught				1.3 in up-draught	1.4 in downdraught
Average turbulence in cloud, 'g'	0.2	0.1	0.1	0.2 - 0.3		0.1	0.1	0.1
Precipitation static. Yes or No	No	No	No	No		No	No	No

/Vertical

Run	1	2	3	4	5	6	7	8
Peak:- Vertical velocity strength. ft. sec^{-1}	(+ 10 (- 3	+ 4 - 8	+ 14 - 4	+ 12 - 8		+ 3 - 8	+ 10 - 2	+ 9 - 7
Average:- (+ ve. sign denotes updraught) (- ve. sign denotes downdraught)	(+ 6 (- 2	+ 2 - 4	+ 8 - 2	+ 8 - 4		+ 2 - $3\frac{1}{2}$	+ 5 - $1\frac{1}{2}$	+ 3 - 4
Crystals. Yes or No	No	No	No	No		No	No	No
Other observations		Vis. 5 yd.	Vis. 5 yd., slight air-frame icing	Vis. 5 yd.			Vis. less than 2 yd., windscreen icing	Vis. 5 yd., 2 yd. in places
Time, hr.	1645	1650	1654 .	1700		1709	1712	1717
Extent, mi.	3.8	2.0	2.0	1.5		3.2	3.0	1.8
Remarks					Film Fogged			
Droplet diameter μ Edge	Largest 30, most 20	Largest 40, most 20	Largest 40, most 20					
Droplet diameter μ Centre	Largest 90, occ. 150-250. Most 20-40.	Largest 200, most 20-40	Largest 100, occ. 490. Most 30-40					

Table 7

23/7/53

Main features of cloud investigated in Flight 7

Run	1	2	3	4	5
Maximum water content, gm.m^{-3}	0.92	> 1.8	> 1.8	> 1.8	
Mean water content, gm.m^{-3}	0.35	0.93	1.03	1.56	
Icing. Yes or No	No	No	No	No	
Mean height, ft. (ICAN)	10146	10306	10160	10184	
Height variation, ft.	+ 29 - 26	+ 94 -166	+ 80 - 95	+ 71 - 84	
Mean airspeed, kt.	177	172	178	175	
Airspeed variation, kt.	+ 1 - 3	+ 4 - 4	+ 7 - 7	+ 6 - 7	
Mean temperature, °F.	27	27	27	27	
Temperature variation, °F.					
Maximum excess temperature in cloud, °F.					
Average turbulence in cloud, 'g'	0.2 - 0.3	0.3 - 0.4	0.3 - 0.4	0.3 - 0.4	
Precipitation static. Yes or No	No	No	No	No	No
Vertical velocity strength. ft. sec^{-1} Peak:-	+ 9 - 3	+ 17 0	+ 25 - 6½	+ 3 - 18	
Average:- (+ ve. sign denotes updraught) (- ve. sign denotes downdraught)	+ 5 - 2	+ 9 0	+ 10 - 3	+ 2 - 9	

/Crystals.

Run	1	2	3	4	5
Crystals. Yes or No	No	No	No	No	No
Other observations	Vis. 20 yd.	Vis. 5 yd. at times	Vis. 5 yd.	Cloud building vigorously in north	Vis. 10 yd.
Time, hr.	1206	1216	1220	1225	1230
Extent, mi.	1.2	1.9	3.0	4.4	
Remarks				Heavy rain in cloud. Vis. 5 yd.	Cloud decaying in south. Film fogged.

Table 8

17/9/53

Main features of cloud investigated in Flight 8

Run	1	2	3	4	5	6	7	8
Maximum water content, gm.m^{-3}	> 1.8	1.8	> 1.8	1.2	Film fogged, record lost	0.92	> 1.8	> 1.8
Mean water content, gm.m^{-3}	0.84	0.86	0.98	0.72		0.61	0.84	1.14
Icing	Slight on windscreen	Moderate on windscreen	Slight on windscreen	Slight on windscreen		Slight on windscreen	Slight on windscreen	Moderate on windscreen
Mean height, ft. (ICAN)	12120	11963	11998	11906		11914	11962	11890
Height variation, ft.	+410 -155	+117 -148	+ 87 - 98	+ 34 - 41		+ 21 - 39	+ 83 - 62	+ 80 -210
Mean airspeed, kt.	176	183	184	188		182	186	189
Airspeed variation, kt.	+ 6 - 6	+ 12 - 6	+ 10 - 8	+ 6 - 6		+ 10 - 10	+ 6 - 7	+ 7 - 8
Mean temperature, °F.	Thermometer unserviceable							
Temperature variation, °F.	Thermometer unserviceable							
Maximum excess temperature in cloud, °F.	Thermometer unserviceable							
Average turbulence in cloud, 'g'	0.1	0.2	0.2 - 0.3	0.2 - 0.3		0.2	0.2 - 0.3	0.3
Precipitation static. Yes or No	No	No	No	No	No	No	No	No

/Vertical

Run	1	2	3	4	5	6	7	8
Vertical velocity strength. ft. sec^{-1} Peak:-	+ 6 -6.5	+ 6 - 7	+ 9 - 8	+ 5 - 6		+6.5 -6.0	+8.0 -9.5	+7.5 -5.5
Average:- (+ ve. sign denotes updraught) (- ve. sign denotes downdraught)	+3.3 -5.1	+2.8 -2.4	+3.8 -5.2	+1.5 -2.3		+2.0 -1.6	+3.5 -3.2	+2.7 -1.7
Overall average:-	+0.9	-0.9	+0.7	-0.5		+0.3	-0.5	+0.6
Crystals. Yes or No	Possibly on western edge	Possibly at western edge	No	No		No	No	No
Other observations		Cloud not very dense	Vis. 20 yd.	Vis. 40 yd.			Vis. 100 yd.	Very bumpy
Time, hr.	1148	1154	1203	1208		1218	1225	1231
Extent, mi.	4.0	4.0	4.0	4.0		3.0	3.5	4.5
Remarks		Cloud rather tenuous			Cassette exhausted. No record for Run 5			
Droplet diameter μ At centre	Largest 320, most 80	Largest 250, most 50	Largest 200, most 40	Largest 320				

Table 9

9/7/53

Main features of cloud investigated in Flight 9

Run	Cell	1	2	3	4	5	6
Maximum water content, gm.m.$^{-3}$	1 2	0	0.32	0.03 0.03	1.80	2.0	1.7 } From icing rates
Mean water content, gm.m.$^{-3}$	1 2	0	0.04	0.02 0.01	1.00	0.66	0.66 }
Icing. Yes or No	Both	No	Yes, slight	Yes, slight	Yes, heavy	Yes, heavy	Yes, heavy
Mean height, ft. (ICAN)	1 2	15076	15201	15027 15052	15060	15247	15274
Height variation, ft.	1 1 2 2	+ 34 - 56	+ 39 - 61	+ 8 - 2 + 3 - 7	+ 20 - 30	+ 93 - 97	+156 - 64
Mean airspeed, kt.	1 2	179	179	180 180	179	177	171
Airspeed variation, kt.	1 1 2 2	+ 2 - 5	+ 2 - 6	0 - 1 + 1 - 1	+ 1 - 1	+ 7 - 4	+ 12 - 5
Mean temperature, °F.	1 2	+10.8	+11.5	+10.4 +10.7	+6.9	+7.6	+11.4
Temperature variation, °F.	1 1 2 2	+0.9 -1.1	+3.0 -2.2	+0.9 -0.5 +0.6 -0.1	+0.9 -0.6	+2.2 -3.5	+4.9 -2.6

/Maximum

Run	Cell	1	2	3	4	5	6
Maximum excess temperature in cloud, °F.	Both	1.2 -1.3 in downdraught	2.8 -2.6 in downdraught	.	+1.4 in downdraught	5.6 in updraught	6.8 in updraught
Average turbulence in cloud, 'g'	Both	0.1 - 0.2	0.1 rising to 0.3 occasionally	0.1 - 0.2	0.1 - 0.2	0.2 - 0.4	0.2 - 0.5
Precipitation static. Yes or No	Both	No	No	No	No	No	No
Vertical velocity strength. ft. sec^{-1} Peak:-	1 1 2 2	+ 8 - 6	+ 8 - 10	0 - 2 + 8 0	0 - 12	+ 18 - 6	+ 1 - 14
Average:-	1 1 2 2	+ 4 - $2\frac{1}{2}$	+ 3 - $4\frac{1}{2}$	0 - 1 + 4 0	0 - 7	+ 11 - $3\frac{1}{2}$	+ 5 - $5\frac{1}{2}$
(+ ve. sign denotes updraught) (- ve. sign denotes downdraught)							
Crystals. Yes or No	Both	Yes	Yes	Yes	No	Few	Few
Other observations		Cloud thin and fibrous		Cloud degenerating	Cloud degenerating	Cloud wispy	New cell, remainder of cloud dropping
Time, hr.	Both	1602	1610	1615	1624	1635	1641
Extent, mi.	1 2	4.0	6.0	1.7 1.0	1.2	2.9	4.5
Droplet diameter μ Centre			Largest 120, occ. 280. Mainly 40-60	Largest 140, occ. 350. Mainly 40-60	Largest 140, mainly 30-40	Largest 200, mainly 60-100	Largest 40, mainly 30
Edge				Largest 80, mainly 20		Largest 40, occ. 80. Mainly 30	

Table 10

Summary of observed and forecast cumulus clouds

Flight, date and time	Base (Observed levels, ft. (ICAN))	Top (Observed levels, ft. (ICAN))	Base (Levels forecast by parcel method, ft. (ICAN))	Top (Levels forecast by parcel method, ft. (ICAN))
1 10/6/53 1628 G.M.T.	3500	14500	1800	9800 generally 14500 occasionally
2 8/7/53 1615 G.M.T.	2000	12000	2200	11800 generally 14000 occasionally
3 14/7/53 1700 G.M.T.	3200	17000 generally 22-23000 occasionally	1800	10500 generally 24000 occasionally
4 14/4/53 1215 G.M.T.	4000	12000	4200	11500 generally 16000 occasionally
5 13/4/53 1200 G.M.T.	3000	9500	3600	7500 to 8500 generally 16000 occasionally
6 4/6/53 1700 G.M.T.	4000	12000	3300	10000 generally 15000 very occasionally
7 23/7/53 1218 G.M.T.	4200	12000	3500	12500 to 13500 very occasionally 15000
8 17/9/53 1209 G.M.T.	1800	14000	2800	10000 generally 17500 occasionally
9 9/7/53 1621 G.M.T.	3000	22000	3700	Very many to 7500, a few to 22000.

Table 11

Observed clouds other than cumulus

Flight, date and approx. time	Height and type of cloud (height ICAN)	Remarks
1 10/6/53 1630 Z	Ac. 9500 ft.	At base of stabilisation of temperature lapse and 50 mb. above a marked wind shear
2 8/7/53 1620 Z	Ac. 10500 ft.	At base of small temperature "stop", no wind shear
3 14/7/53 1700 Z	None	
4 14/4/53 1215 Z	None	
5 13/4/53 1200 Z	Sc. 7000 ft.	At base of small temperature "stop", no wind shear
6 4/6/53 1700 Z	Ac. 9500 ft.	At base of small temperature "stop", no wind shear
7 23/7/53 1220 Z	Sc. 7000 ft.	At base of very small temperature "stop", no wind shear
8 17/9/53 1210 Z	Sc. 4000 ft. Sc. 7500 ft. Ac. 9300 ft. Ac. 10500 ft. Ac. 11000 ft.	All at bases of very small temperature "stops," no wind shear
9 9/7/53 1620 Z	Ac. 9700 ft. Cs. 22000 ft.	Both at bases of small temperature "stops"

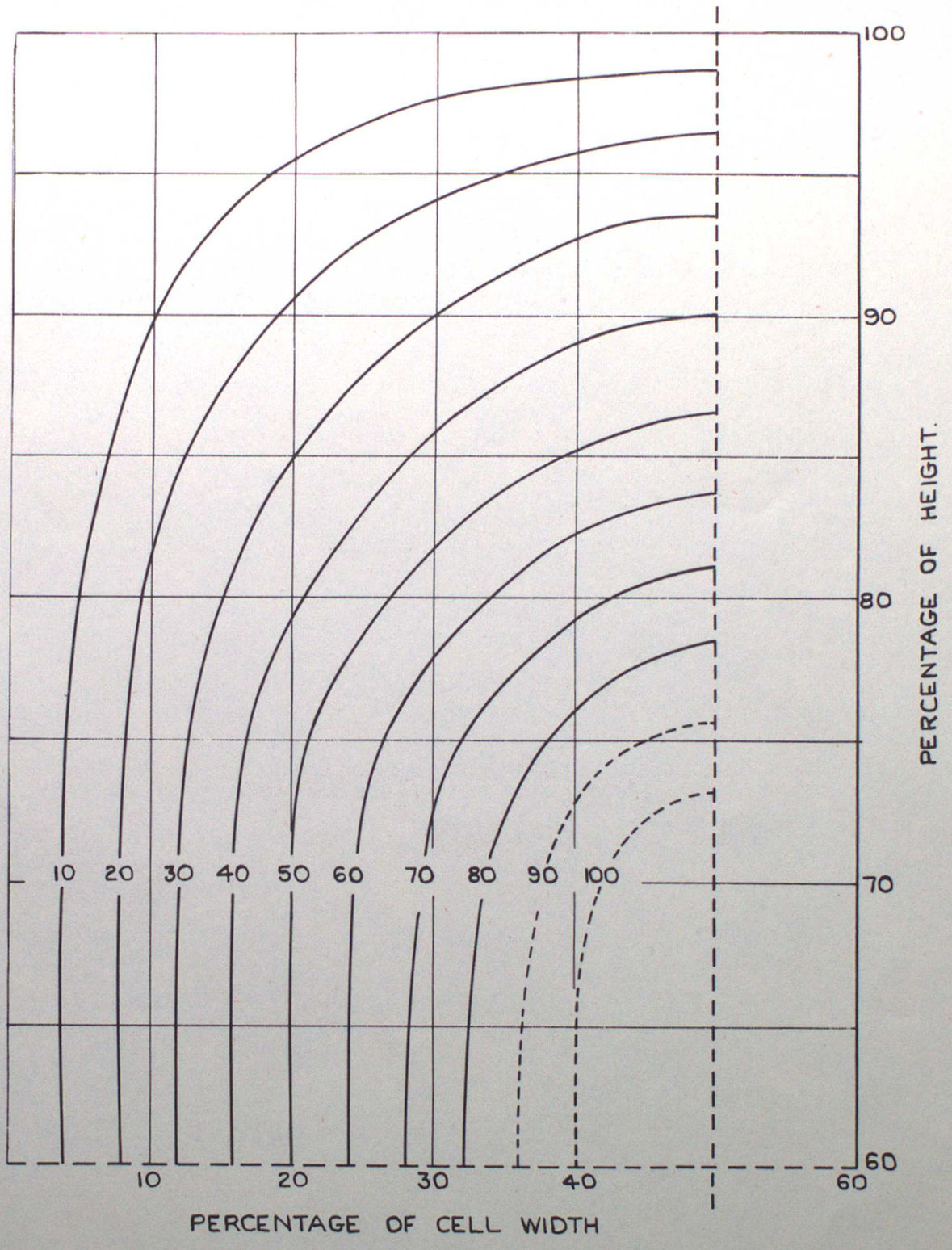


FIG I. IDEALISED DISTRIBUTION OF WATER-CONTENT IN A CUMULUS CLOUD EXPRESSED AS A PERCENTAGE OF MAXIMUM REALISABLE WATER-CONTENT ON THE ASSUMPTION OF ADIABATIC LIFTING.

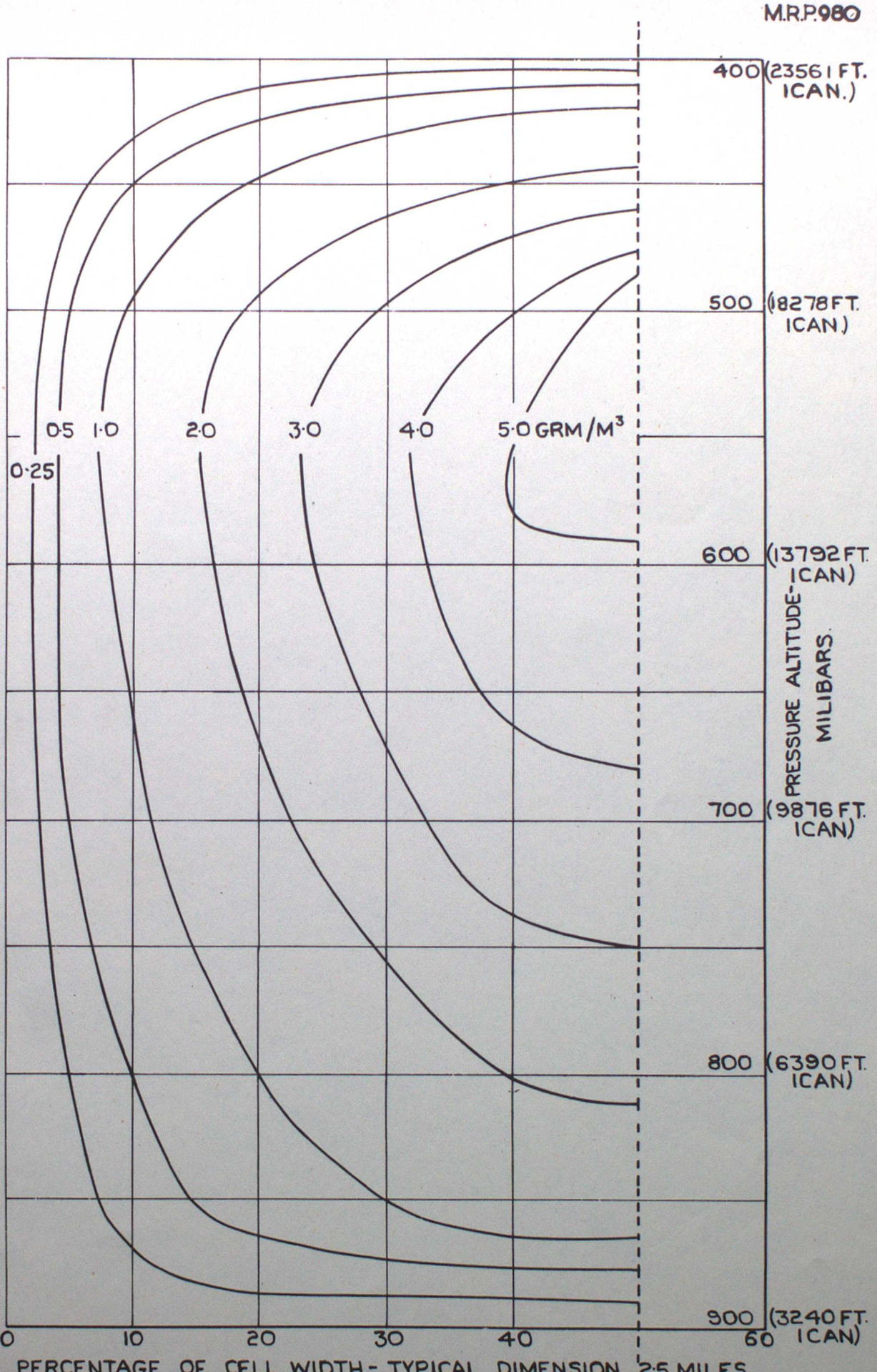
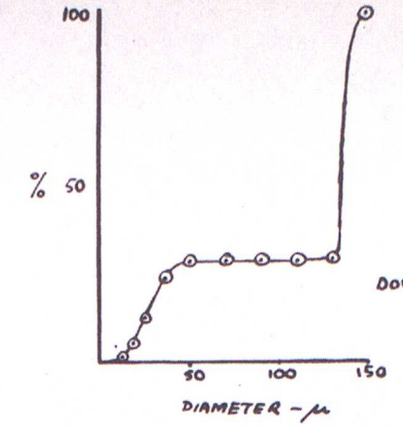


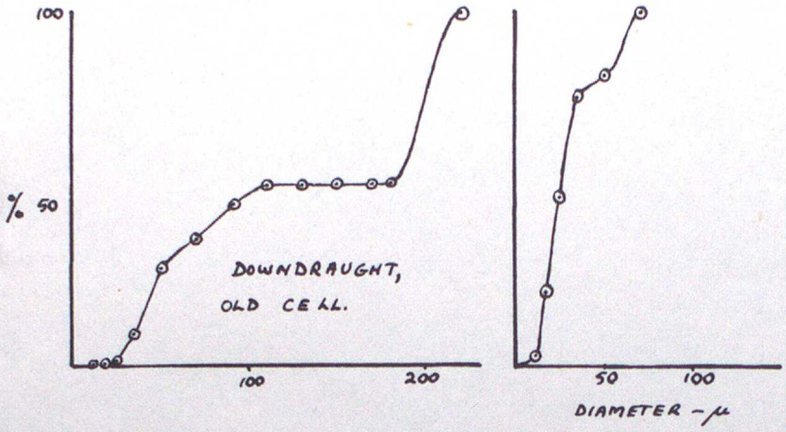
FIG. 2. DISTRIBUTION OF WATER-CONTENT TO BE EXPECTED IN TYPICAL CUMULUS CLOUD HAVING BASE AT A HEIGHT OF 900MB. (3240 FT.) AND A TEMPERATURE OF 60°F AND HAVING TOP AT 400 MB. (23561 FT.)

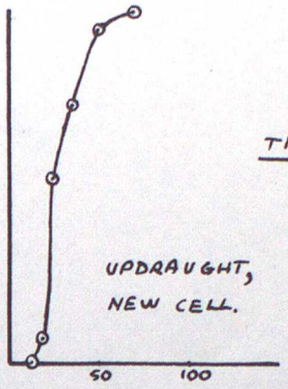
AIR TEMPERATURE 10°F, HEAVY ICING OF AIRFRAME THROUGHOUT.



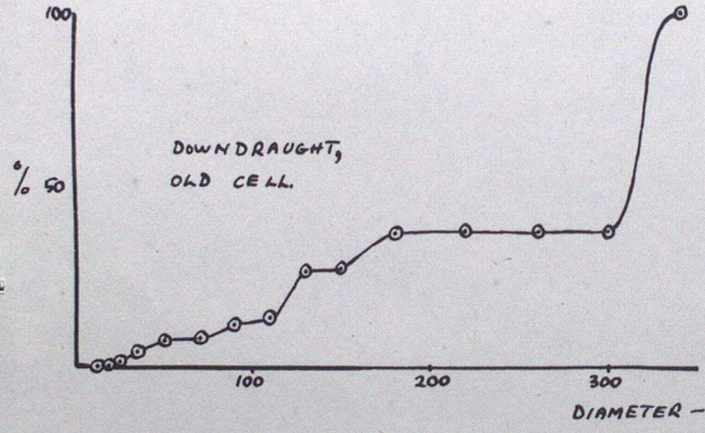
TRAVERSE 2, 1153 Z

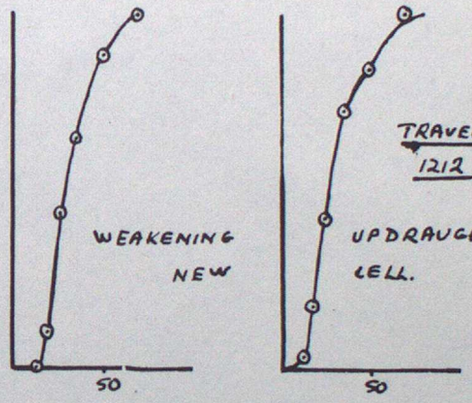
DOWNDRAUGHT, ESTABLISHED CELL.



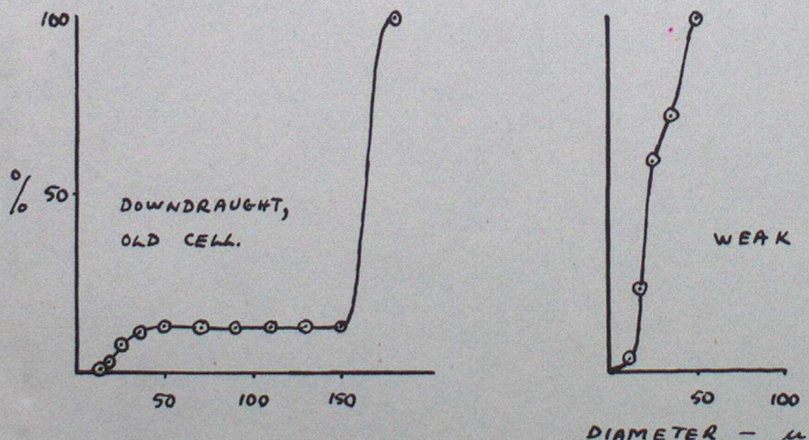


TRAVERSE 3, 1200 Z

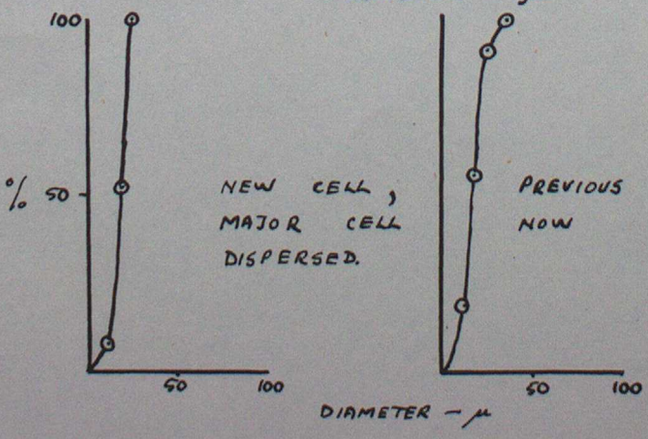




TRAVERSE 5, 1212 Z



TRAVERSE 7, 1226 Z.



TRAVERSE 9, 1244 Z.

FIG. 3 DROPLET DIAMETER DISTRIBUTION BY CUMULATIVE VOLUME, LARGE CUMULUS CLOUD OF 14.4.63